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Process Monitoring in Solar Cell Manufacturing

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Process Monitoring in Solar Cell Manufacturing

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Introduction

The photovoltaic (PV) industry has grown very rapidly in the last few years. It is expected that the PV industry can now benefit as a whole from collective research, standardization, and process control. An example of the success of this cooperative methodology is the Si-based microelectronics industry in which standardization and process control have proven to be valuable for improving reliability and throughput in manufacturing. Hence, as the annual production increases further, the introduction of process control and monitoring in PV manufacture is imminent. The PV industry is already using some degree of process monitoring, but a full-fledged process control has to await development of suitable measurement techniques.

In this paper, we describe a new method that is capable of in-line monitoring of several solar cell process steps such as texturing, AR coatings, and metal contact properties. The measurement technique is rapid and specifically designed for solar cells and wafers. The system implementing this new concept is named "PV Reflectometer." The idea was originally conceived several years ago and the principle of the method has been demonstrated for some simple cases in (1,2). Recently, this method has been improved to be more suitable for commercial applications. For completeness, the paper first includes a brief review of the process control requirements and the common monitoring methods in solar cell production.

Requirements of solar cell process monitoring

Solar cell fabrication involves many process steps (see Table 1, columns 1 &2). Specifically, monitoring is needed for:

1. Ingot or incoming wafer quality – the parameters to be measured are the resistivity, minority-carrier lifetime (τ) or diffusion length (L), defect density, impurity concentrations, surface roughness, and cleanliness/contamination
2. Texture quality
3. Junction depth (sheet rho)
4. AR coating thickness(es) and refractive indices
5. Metallization parameters (area, thickness, width, back-contact properties)
6. Cell parameters.

It is clear that the processes to be monitored are similar to those used in the microelectronics industry and that many of the process steps can be monitored using non-contact optical methods. Whereas the microelectronics industry is well equipped with a great deal of instrumentation, unfortunately these methods are not well suited for solar cell production. Concomitantly, there is now an intense search for proper techniques for monitoring purposes in the PV industry. It is in general desirable to have noncontact optical techniques.

Difficulties in using conventional techniques for PV monitoring

Column 3 of Table 1 shows a number of techniques, originally developed for the semiconductor industry, which are now used for solar-cell process monitoring. These measurement methods are not well suited for solar cell industry because:

1. Solar cells (and substrates) have rough or textured surfaces/interfaces
2. Equipment is expensive
3. Measurements are slow for high throughput facilities, and
4. Measurements are made on small areas. In solar cell monitoring, it is important that the properties of the entire wafer be measured. This is because typical processing introduces strong nonuniformities and, in many cases, local measurements can yield meaningless values as far as process monitoring is considered.

Table 1. A list of the major process steps, parameters that are monitored, and the monitoring techniques used in solar cell fabrication. Also indicated (by X) are the steps that can be monitored using a reflectometer.

Process or monitor step	**Parameter(s)**	**Technique**	**Possibility of using Reflectometer**
Crystal growth (Ingot Quality)	τ	PCD	
Wire Sawing Quality/wafer cleanliness	Surface Roughness/residue		X
Texturing	Texture Height	SEM/Optical microscopy/Reflectance	X
Electronic Quality of wafers	L/τ	SPV/PCD	
Junction Depth	Sheet Resistance	4 Point Probe, groove and stain	
Defect Density	Dislocation Density	Chemical Delineation / TEM	
Impurity Concentration		FTIR, NAA, SPV, DLTS	
AR-Coating	Thickness, Refraction Index	Ellipsometer/Interference	X
Metallization	Line Width	Optical/SEM	X
I-V of Cell	V_{oc}, J_{sc}, FF	Standard I-V measurement	

It is a common experience in commercial solar cell fabrication that measurements on solar cell wafers yield unreliable values. Hence, in most cases, the solar cell industry uses additional “control wafers” in each process step that are polished on one side. However, the use of such “dummy” wafers has many disadvantages, and limits the degree of process control that can be implemented on a production line.

Basic principles and the measurement approach

The 4th column of Table 1 shows various process steps which can be monitored by means of a reflectometer. However, because conventional reflectometers are small-beam instruments, they cannot measure a large-area wafer. One way to overcome this limitation is to scan the wafer. This approach is used in PVSCAN (3,4). Although, such an instrument can yield a great deal of information, the scanning methods are inherently slow.

We have developed a new noncontact technique (PV Reflectometer) for monitoring a number of processes in a solar cell production facility. It can measure the surface roughness, surface cleanliness or contamination, texturing, AR coating properties, and metallization parameters. To overcome the difficulties intrinsic to the conventional methods, the new measurement concept is based on the reciprocity principle in optics. Figure 1 illustrates the reciprocity principle in that the two cases shown are optically equivalent. Figure 1(a) shows the incident light is normal to the sample and the reflected (scattered) light is collected through all the angles, and Figure 1(b) shows the light incident from all the angles and collected normal to the sample. The approach of Figure 1b confers many advantages, including ease of large-area illumination and simplification of the signal collection—features that can greatly enhance the S/N ratio to render a measurement fast. The next section will show how those are made practical.

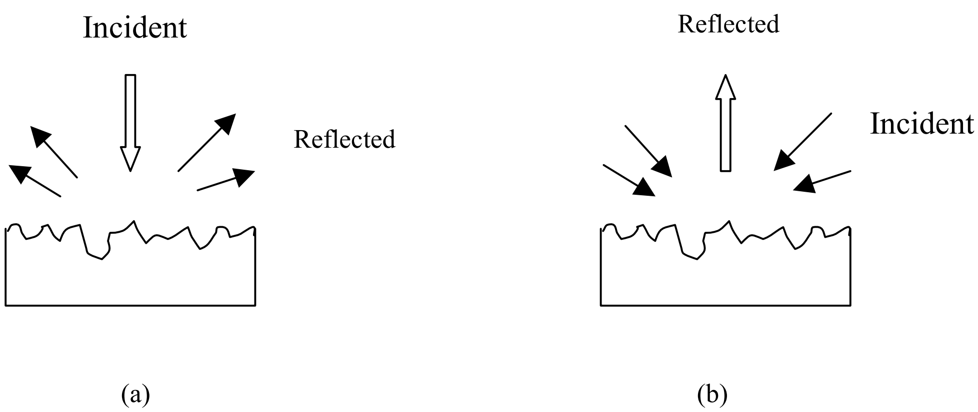

Figure 1. Illustration of the conventional illumination approach (a) and the reciprocal approach (b).

The PV Reflectometer employs the reciprocity principle similar to that in Figure 1b to illuminate the entire wafer. It measures the total reflectance of the sample as a function of wavelength, and uses different segments of the curve to extract information about the front-surface and back-surface properties. This methodology is illustrated in Figure 2. This figure shows a typical reflectance plot of a textured, mc-Si solar cell with an AR coating and front and back metallizations. Here, λ_0, R_0, R_b and $\Delta\lambda$ are used for determining the AR coating thickness, metallization fraction, backside metallization quality, and texture parameters, respectively.

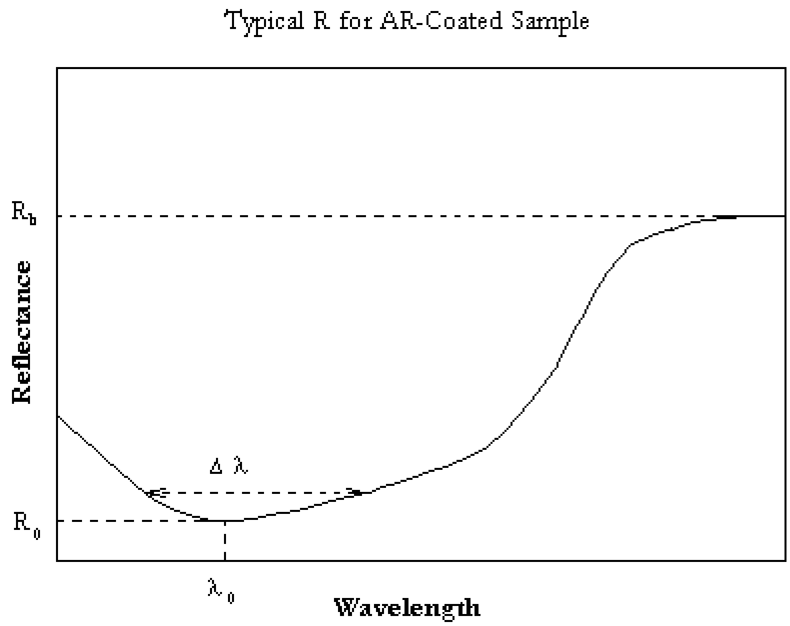

Figure 2. Illustration of the various parameters of a reflectance plot used for process monitoring

Description of the equipment

The reflectometer (see Figure 3) consists of a highly absorbing spherical dome, about 12—18 inches in diameter, with openings at the top and at the bottom. The bottom side has a square flange, within which the test sample is placed. The sample is placed on a platform in a way that the signal, consisting of the reflected light seen by the detector, is due only to the sample. The entire system is designed to eliminate all the possible scattering of the light except by the test wafer. The topside of the dome has a lens and aperture assembly that couples the light reflected from the sample into the optical fiber. The other end of the fiber feeds into a low-resolution monochromator, whose output is detected by a Si photo-diode. If the fiber is taken out of the optical path, one can observe a reflected image of the sample. This image can be further used to map the sample, giving more detailed spatial information.

The monochromator drive, data taking/handling, calibration, and the system control are done by a computer. The system operates in a spectral range that allows reflections from the front and the backside of the cell to be monitored.

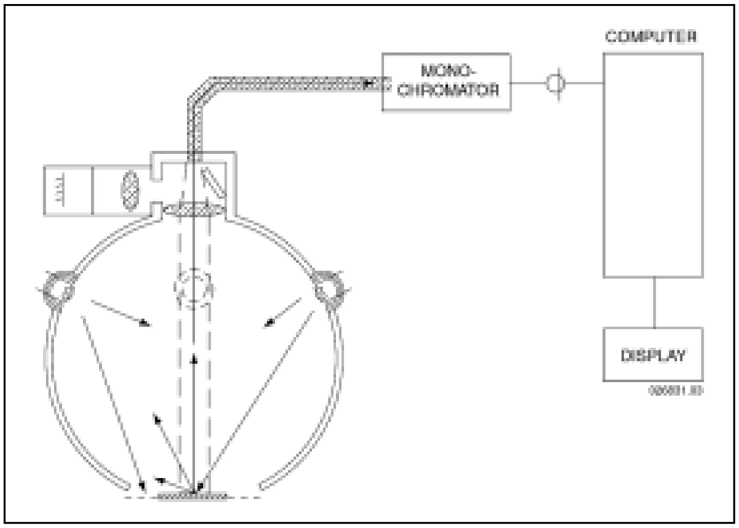

Figure . A schematic of the PV Reflectometer

Using the reflectometer

The reflectometer can be used for all the process monitoring steps shown in table 1. These are briefly described below.

a. Monitoring the sawn wafer and texture quality by surface reflectance
The solar industry usually uses wafers with textured or rough surfaces to reduce overall reflectance of the solar cells, and trap light to enhance its absorbance. Typically, the sawn wafers are cleaned and etched at room temperature in a caustic etchant to remove the surface damage. Any residual damage can be very detrimental to the junction quality of the cell and degrade the bulk material quality by generating dislocations during the cell processing.

The next process step may consist of surface preparation involving texture-etching the wafers in a hot sodium- or potassium-based hydroxide solution. This solution is an anisotropic etch that produces surface structures by exposing (111) crystallographic faces. For example, it produces pyramid-shaped surface texture on (100) wafers. The size and the height of the texture depend on many parameters, including concentration of the hydroxide, temperature of the etch bath, pH of the solution, resistivity of the wafer, presence of surface damage (such as from sawing) on the wafer, and on the number of samples etched (because the composition of such a bath changes with the formation of silicates produced by the dissolution of Si).

Because the texturing properties depend on so many parameters, this process is apt to result in significant variations from batch to batch and within the same batch of wafers, if no monitoring is incorporated. These variations in the surface quality lead to variations in the photocurrent (J_{ph}) of the cells. Furthermore, because it is a common practice in the industry to combine texture etching with the saw-damage removal step (as a cost-reduction strategy), texture etching is a crucial step in cell production. An incomplete removal of damage can have a tremendous effect of degrading the fill factor (FF) and the open-circuit voltage (V_{oc}) of the cells. Therefore, it is important to measure the surface quality of the wafers before they enter a cell production. Currently, the PV industry does not have a suitable method for monitoring texture quality.

The reflectance of the wafer can be used to monitor the quality of both the sawn and the textured wafers.

b. Measuring AR coating thickness
A minimum or null of the reflectance is used to determine the thickness of the AR coating. However, an AR-coated wafer with rough/textured surface exhibits a broadened minimum. This may require a high S/N ratio to magnify and search for the true minimum. Our reciprocity illumination will result a high detection sensitivity to avoid the problem. PV Optics is used to relate the reflectance and the AR coating parameters.

c. Front surface reflectance/metallization fraction
An AR-coated solar cell, with front metallization, will display a reflectance minimum whose amplitude is related to the fraction of the cell area covered by the metal. It is possible to attain many parameters of the front metallization using illumination with different angular distributions.

d. Back-side reflectance
The reflectance of a solar cell in the long wavelength region can be related to the quality of the back contact. For instance, a good quality Si-Al contact should have very high reflectance. A properly alloyed Al can be controlled to have a reasonably sharp interface and a high reflectance. However, formation of a back-surface field lowers the back reflectance by providing a refractive index gradient at the interface. *PV Optics* allows us to perform calculations to relate the reflectance to the alloy quality of the back contact.

Preliminary Results

Figure 5 shows some results produced on a laboratory system in arbitrary unit using samples from a PV company. The samples are taken at various stages of the cell fabrication—after pre-etch cleaning, after texture etching, and after AR coating. The data include:

1. Reflectance of a commercial 4.5-in. x 4.5-in., mc-Si wafer after sawing and cleaning
2. Reflectance of a commercial 4.5-in. x 4.5-in., mc-Si wafer after texture-etching
3. Reflectance of a commercial 4.5-in. x 4.5-in., mc-Si wafer after the TiO_2 deposition. The measured thickness of TiO_2 ranges from 794–858 Å.

The results show that sawing and wafer cleaning have a tight control, while texturing has a significant variation from wafer to wafer. The AR coating mitigates some of the variation. The average thickness of the coating ranges from 794–858 Å. The current system can accommodate samples as large as 6 in. x 6 in. A typical run of the laboratory system now takes about 15 seconds per sample for the entire measurement.

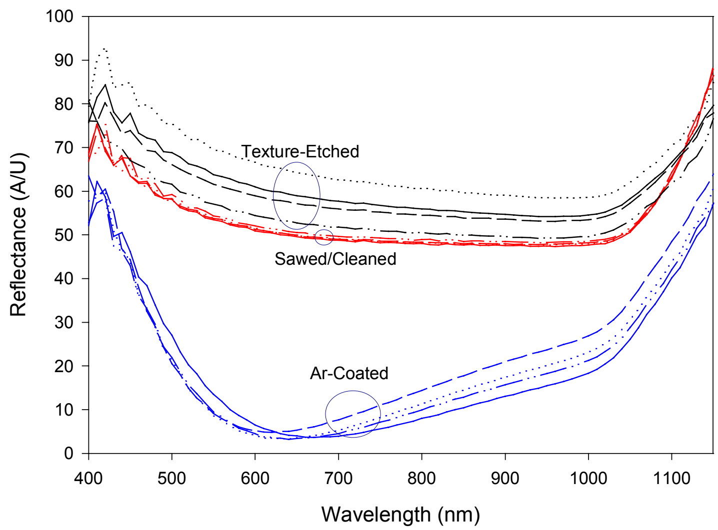

Figure 4. Reflectometer results on three groups of commercial PV-Si wafers (4.5-in x 4.5-in) at different stages of solar cell fabrication.

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